

# Cassini Ring Plane Crossings: Hypervelocity Impact Risks to Sun Sensor Assemblies†

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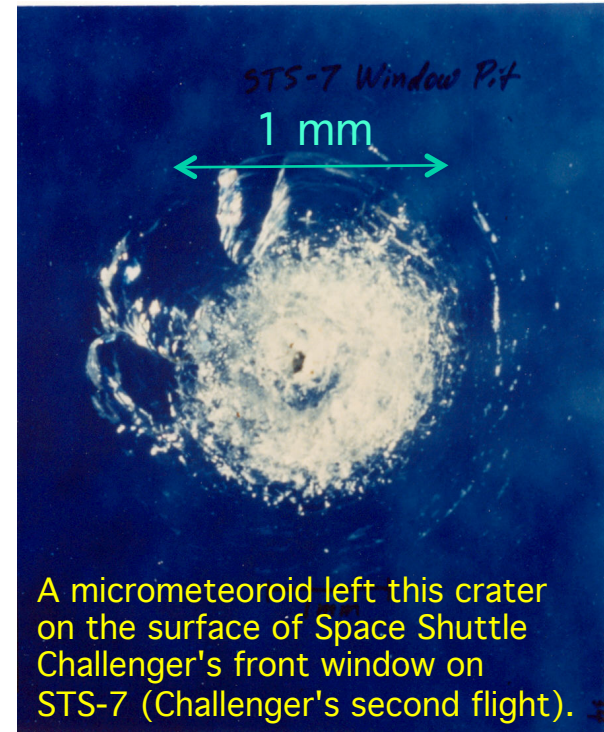
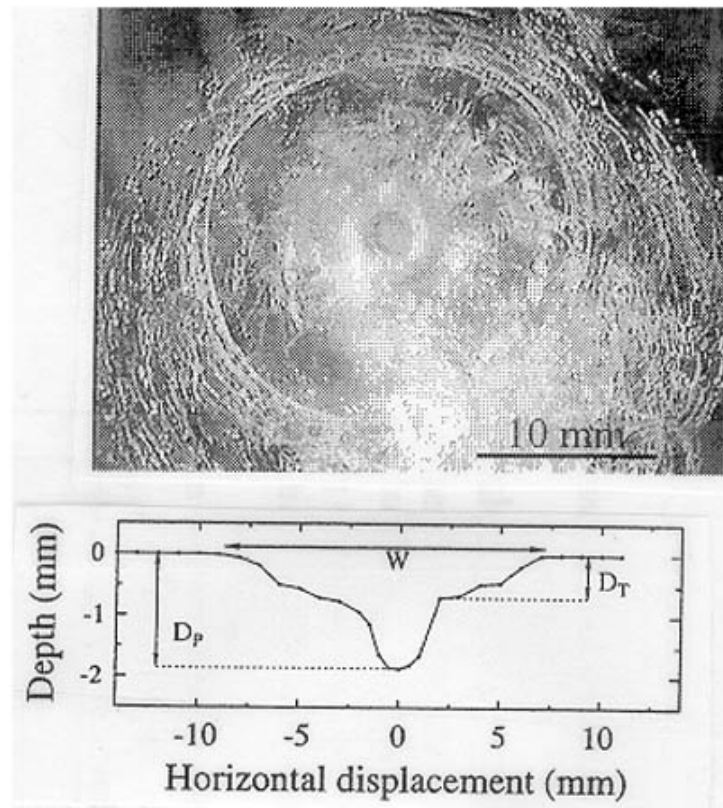
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\*With significant supports from Tom Burk and Dave Seal.

# Damage due to Micro-particle Hyper-Velocity Impact (HVI) on Glass Surfaces

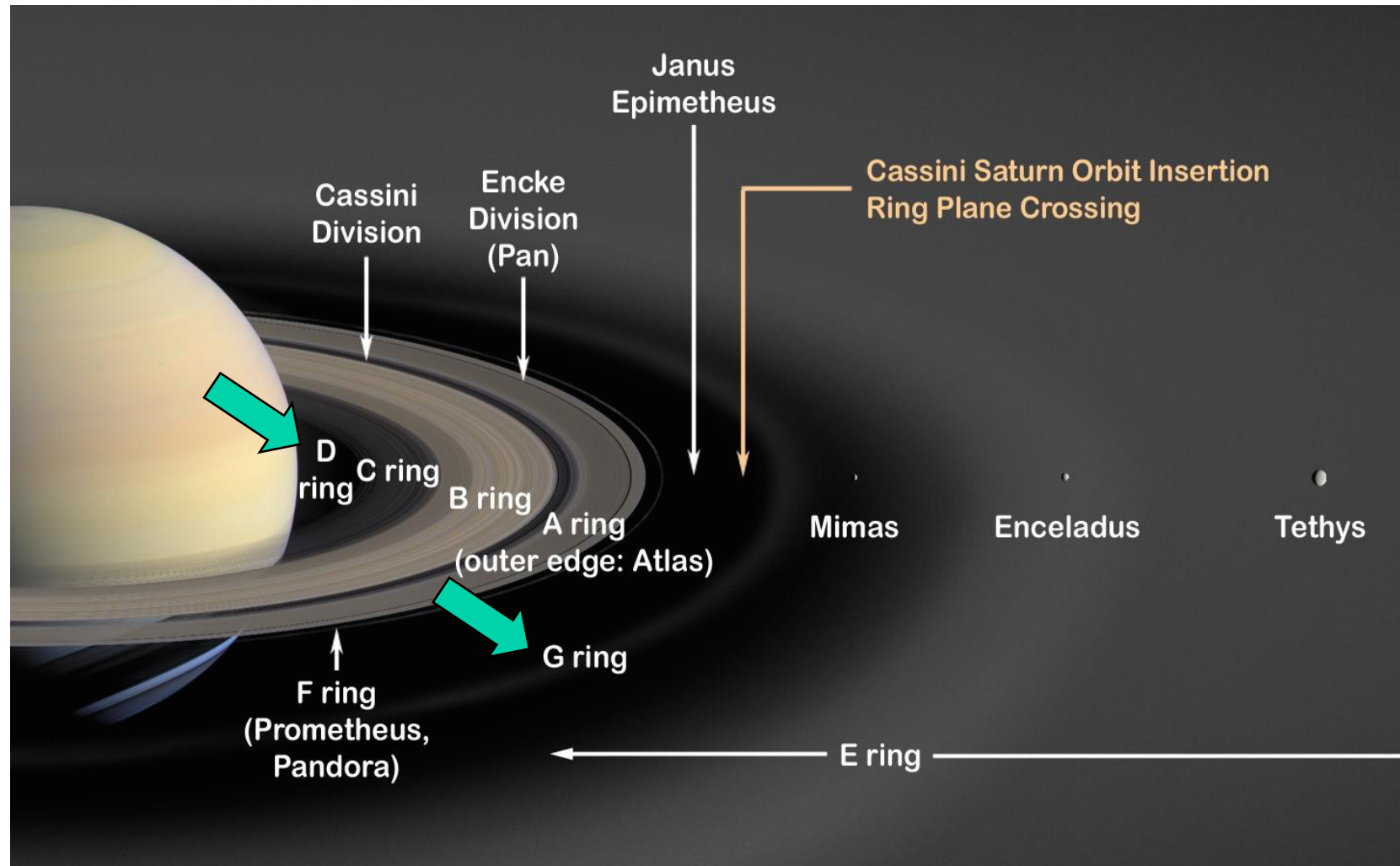
- Image of an impact crater:<sup>[11]</sup>
  - Projectile: 1-mm diameter Aluminum sphere travelling at 5.11 km/s
  - Target: 2.5-cm thick soda lime glass blank, “normal” impact

Note: Vertical scale has been exaggerated



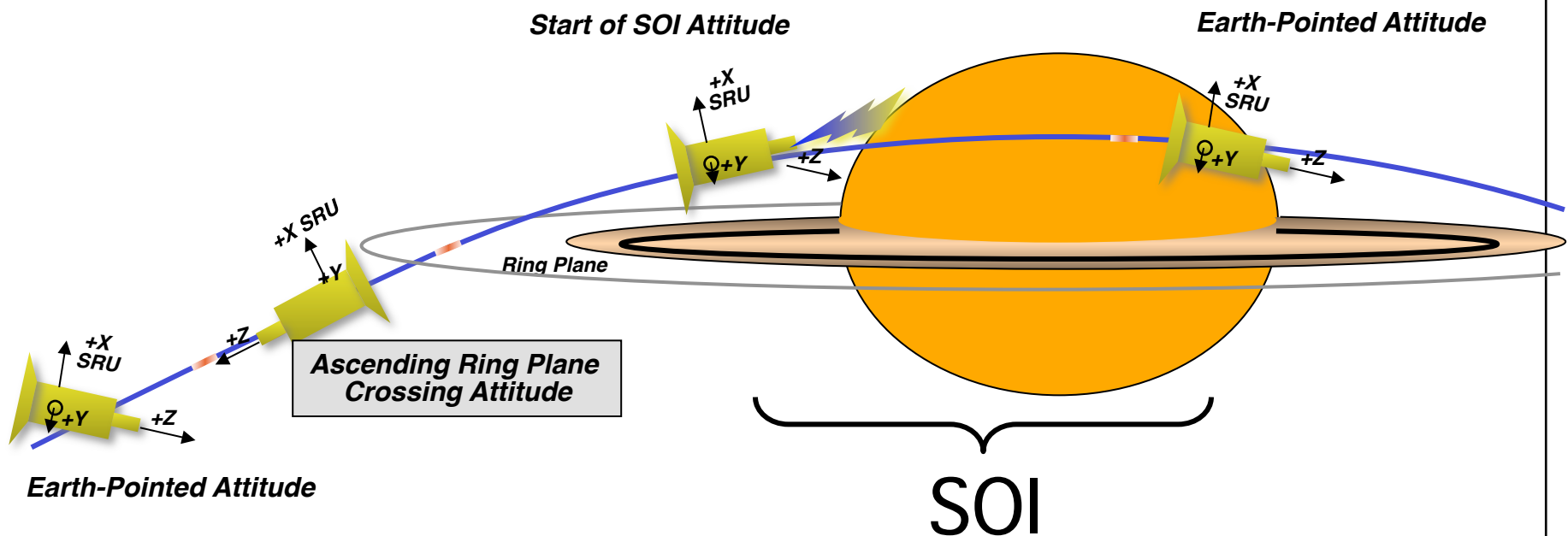
# Focus of this study

- F/G ring (Saturn Orbit Insertion, SOI, 2004), and
- D ring (proximal orbits, 2017)



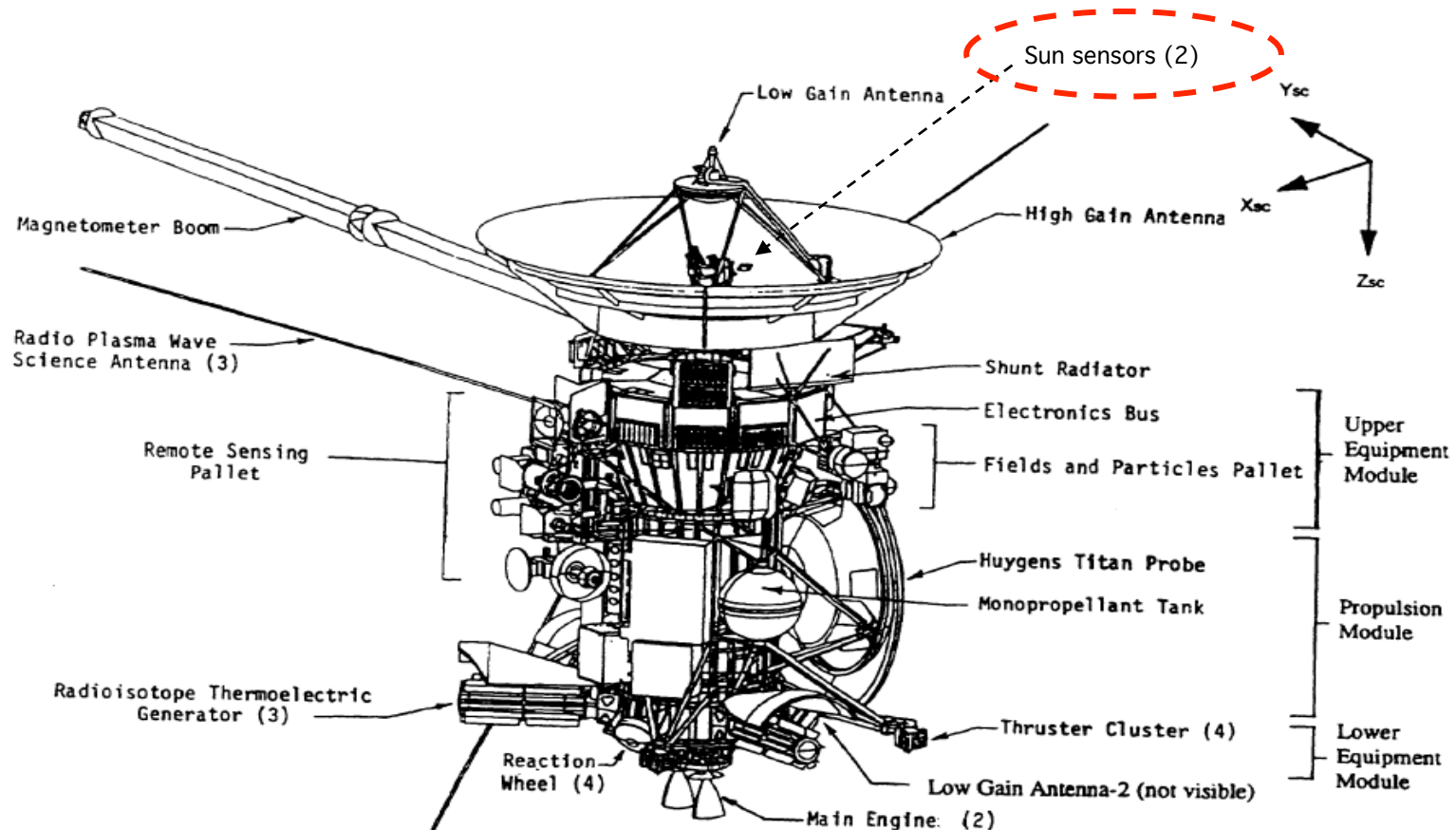
## Ring Plane Crossings at Saturn Orbit Insertion (July 1, 2004): Risks to Sun Sensors

- Two ring plane crossings happened before and after the Saturn Orbit Insertion (SOI) burn:
  - During these crossings, the HGA was pointed into the ring dust particle flow
  - The Sun Sensor Heads (SSHs) are co-located with the HGA. HVI risk to the SSA was assessed in 2004 and reported in this work



# Sun Sensors location on the HGA

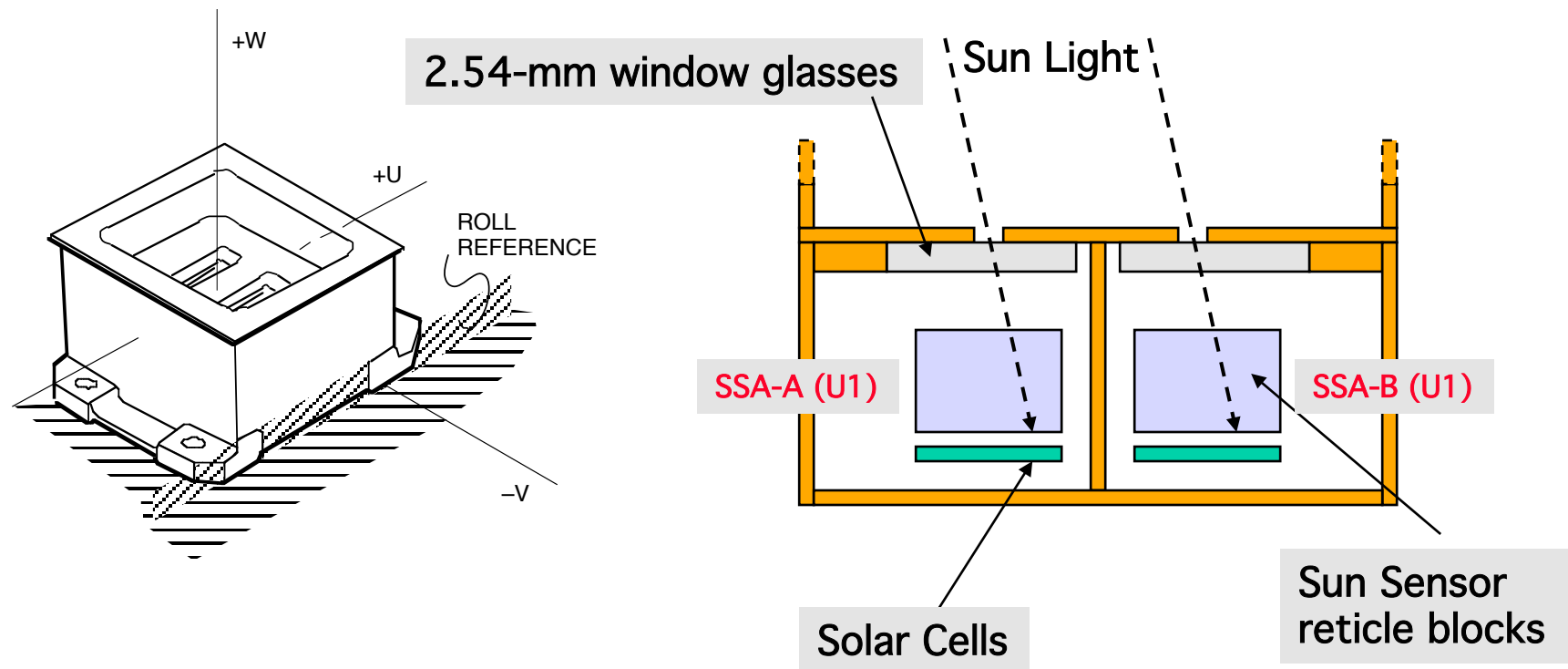
- Cassini Spacecraft Cruise Configuration (MLI and main engine cover have been removed from the image for clarity)



The high gain antenna (HGA) is relatively insensitive to impacts of millimeter-sized (or smaller) dust particles. Even the antenna feeds can tolerate a peppering of millimeter-sized holes with almost no loss in transmission capability. Details are given in paper.

## Sun Sensor Window Glasses

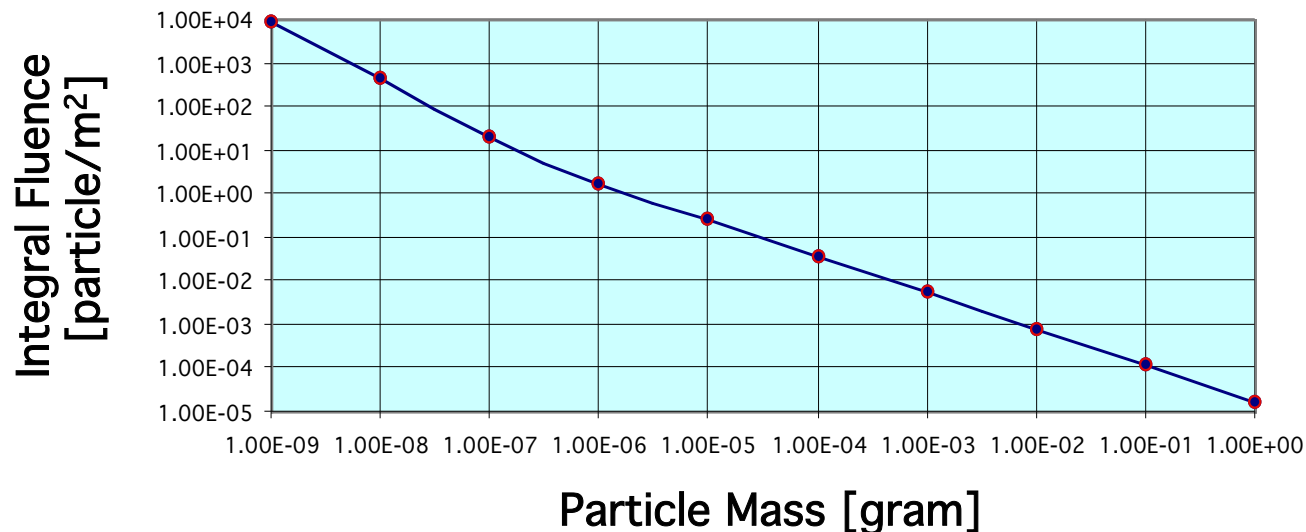
- Two “window” glasses are placed between the reticles and the aluminum alloy housing



# Environmental Design Requirements

- Applicable SOI Environmental Design Requirements [12]
  - Section 3.3.4 Solid Particle
    - 3.3.4.1 Penetration
      - The flight system shall be designed to ensure a 95% probability of mission success in the solid particle environment specified in Ref. 12 “Fluence Distributions for Solid Particles Penetration”
      - For Saturn ring particles: The Integral Fluence for all orbits (particles/m<sup>2</sup>) is:

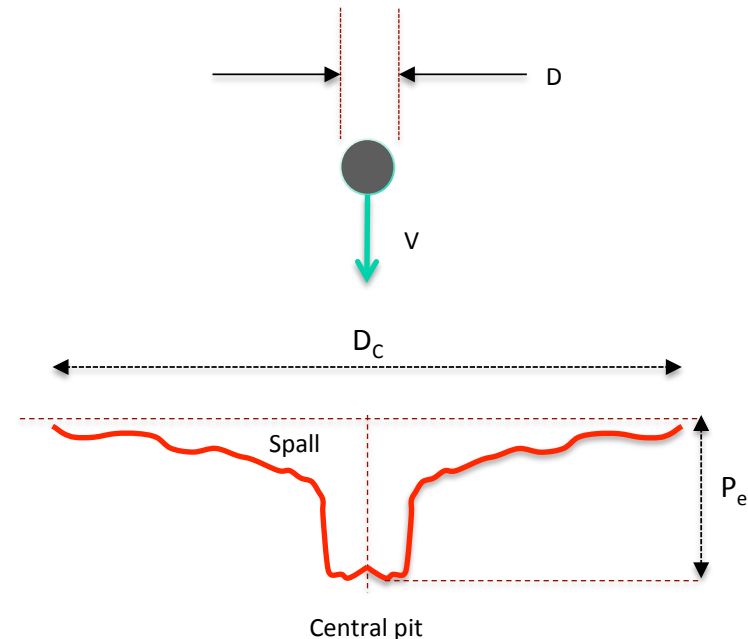
Integral Fluence from ALL orbits [Reference 12]



# SSA HVI Risk Types Addressed

- Risks to Sun Sensor Assemblies during HGA-to-RAM SOI ring plane crossings:

1. **Penetration failure** of the SSA cover glass due to HVI impacts by ring dust particles
2. Degraded SSA performance (**optical attenuation**) due to HVI-generated impact craters
3. Degraded SSA performance (optical attenuation) due to HVI-generated impact craters caused by **ricochet debris** from particle impacts with HGA dish



An HVI-generated crater and its dimensions:

- $D$  is the diameter of the projectile
- $V$  is the velocity of the projectile
- $P_e$  is the penetration depth of the HVI crater
- $D_c$  is the diameter of the spalled surface crater

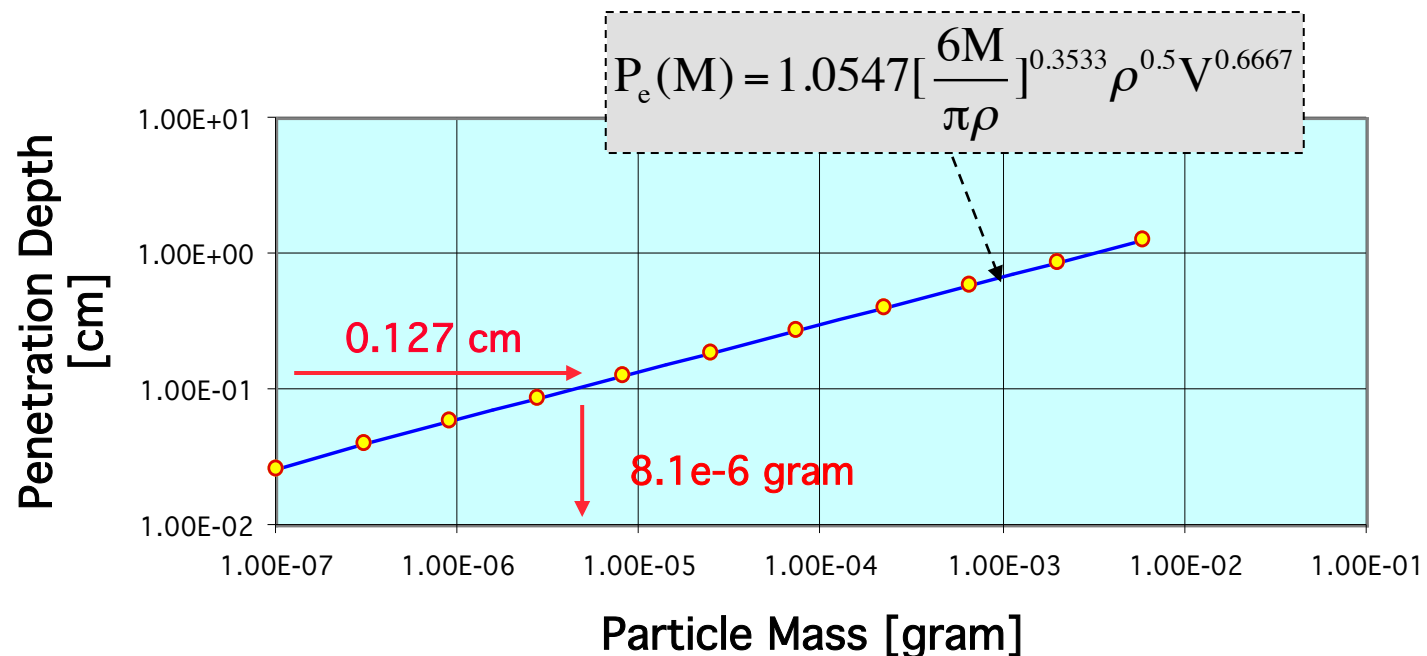
## Penetration (1 of 3)

- The SSA window glass thickness is 2.54 mm
  - A crater depth that is 1/2 this thickness is considered a penetration failure (Ref. 13)
- Penetration depth in glass due to HVI: Test-verified relation is given below (Ref. 11). For the SOI scenario, we have
  - $\rho$  = density of micro-particle (gram/cm<sup>3</sup>) = 0.5
  - $V$  = impact velocity (km/s) = 17.1
  - $M$  = dust particle mass (gram)
  - $P_e$  = depth of crater (cm)

$$P_e = 1.0547 \left[ \frac{6M}{\pi\rho} \right]^{0.3533} \rho^{0.5} V^{0.6667}$$

## Penetration (2 of 3)

- Variation of penetration depth ( $P_e$ , in cm) with particle mass ( $M$ , in gram):



- Dust particles with mass  $\geq 8.1e-6$  gram will create a crater with a depth  $\geq 1.27$  mm (half the thickness of the SSA window glass)

## Penetration (3 of 3)

- The exposed SSA window glass area ( $A_{SSA}$ ) =  $4.6e-4 \text{ m}^2$  (combined area of the two SSH)
- Integral fluence ( $F$ ) for particles with mass sizes  $\geq 8.1e-6 \text{ gram}$  is  $< 0.303 \text{ particles/m}^2$
- Number of particles with this size range for the entire mission:  
$$= A_{SSA} \times F = 1.4e-4 \text{ particles} \ll 1$$

*It is highly unlikely that the Cassini SSA cover glass will encounter a dust particle with mass  $> 8.1e-6 \text{ gram}$*

## Optical Attenuation (1 of 2)

- To compute the crater diameter:<sup>[11]</sup>

$\rho$  = density of dust (gram/cm<sup>3</sup>) = 0.5

$V$  = impact velocity (km/s) = 13.6

$M$  = dust particle mass (gram)

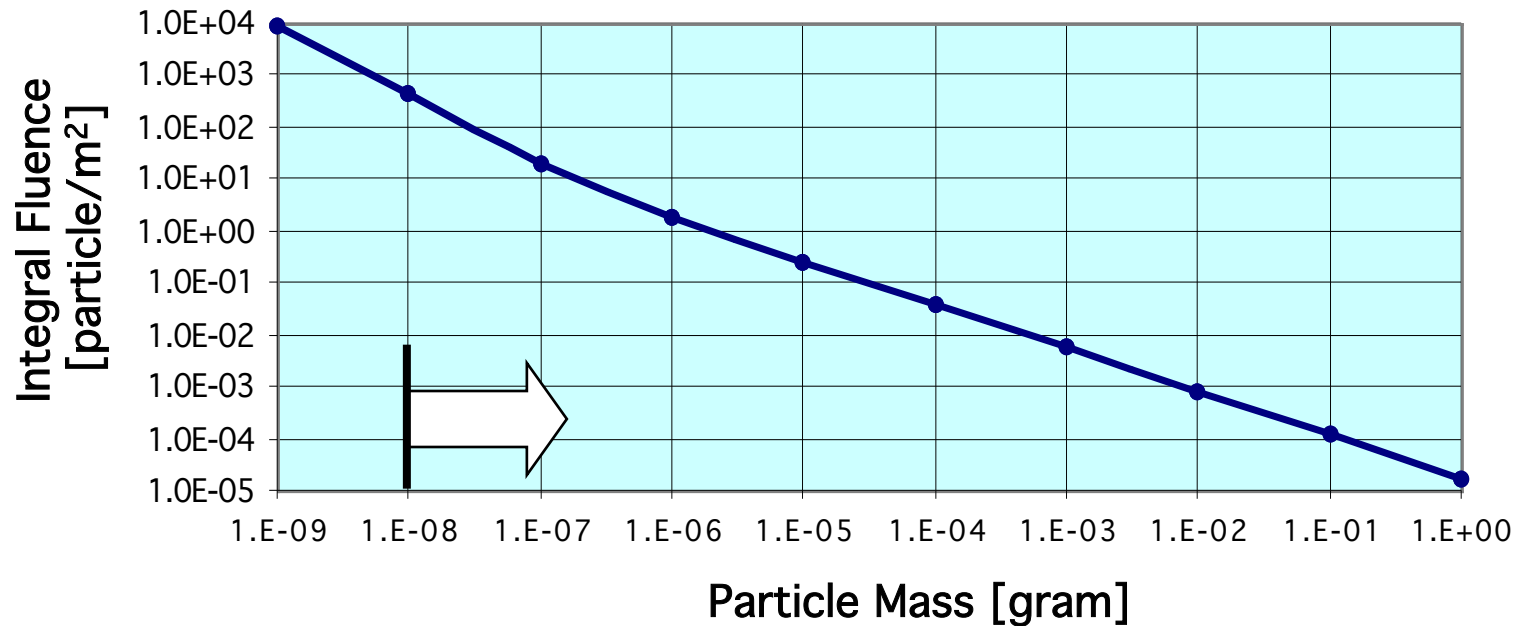
$D_e$  = crater diameter (cm)

$$D_e = 8.037 \left[ \frac{6M}{\pi\rho} \right]^{0.3533} \rho^{0.5} V^{0.6667}$$

- At hypervelocity (>10 km/s), experimental results<sup>[13]</sup> indicated that less than 10% of the circular crater area has fractures that caused total light reflection:
  - This study assumed that the entire crater area “blacked-out” light
  - SSA vendor (Adcole) estimated that only craters with diameter that is >0.762 mm will affect SSA output

## Optical Attenuation (2 of 2)

- The particle mass that creates craters with diameter  $\geq 0.762$  mm is  $\geq 1.0\text{e-}8$  gram (using formula from last page)



- Optical attenuation due to Ring Dust Particles:

$$\text{Attenuation}_{\text{ring}} = \frac{2}{A_{\text{SSA}}} \int_{M=10^{-8}}^{M=10^0} \left[ -\frac{dF_{\text{ring}}(M)}{dM} A_{\text{SSA}} \right] \left[ \frac{\pi D_e^2(M)}{4 \times 10^4} \right] dM$$

Double per requirement  
and to be conservative

= 0.69% (= 1.07% if  $\rho$  is quadrupled)

**(Insignificant)**

## Crater-related Optical Attenuation Based on Other Empirical Formulae

- Beside Ref. 11, other empirical relations between the crater diameter and the density of the projectile, the mass of the projectile, and the relative velocity are also available in the literature
  - For particle mass within the range of  $1.0\text{e-}9 < M < 1.0\text{e-}3$  gram, crater diameter predicted by Ref. 18 (Burt and Christiansen, 2003) produced the most conservative result. Crater diameter predicted by Ref. 11 produced the second most conservative result

$$D_c = 8.037 \left[ \frac{6M}{\pi\rho} \right]^{0.3533} \rho^{0.5} V^{0.6667}$$

Flaherty (Ref.11), 1970

$$D_c = 30.9 \left[ \frac{6M}{\pi\rho} \right]^{0.443} \rho^{0.44} V^{0.44}$$

Edelstein (Ref. 17), 1995

$$D_c = 9.656 \left[ \frac{6M}{\pi\rho} \right]^{0.394} \rho^{0.373} V^{0.915}$$

Burt and Christiansen (Ref. 18), 2003

$$D_c = 5.3 \left[ \frac{6M}{\pi\rho} \right]^{0.3533} \rho^{0.5} V^{0.6667}$$

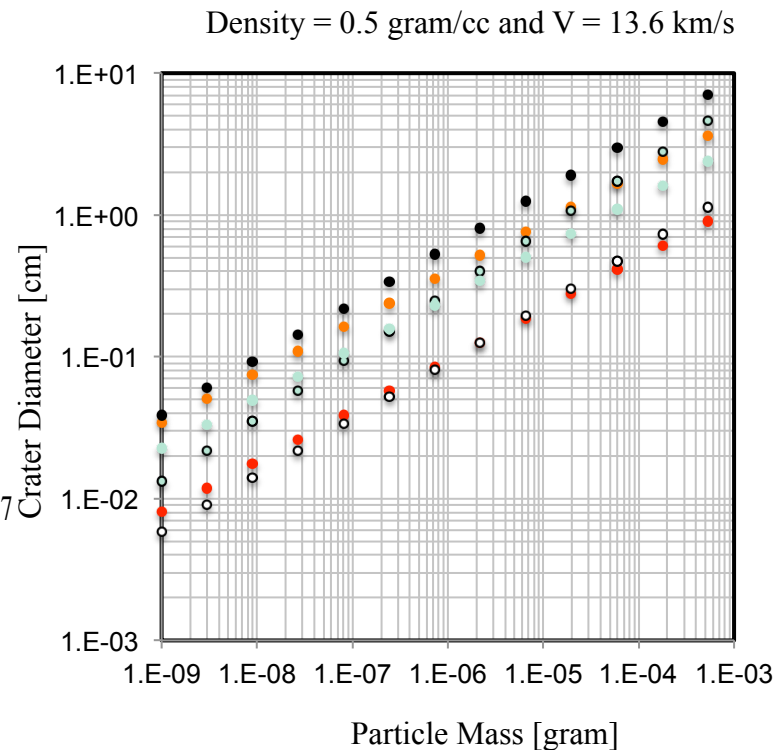
Christiansen (Ref. 13), 2009

$$D_c = 2.16 \left[ \frac{6M}{\pi\rho} \right]^{0.359} \rho^{0.784} V^{0.727}$$

Paul, Igensbergs, and Berthoud (Ref. 19), 1997

$$D_c = 8.49 \left[ \frac{6M}{\pi\rho} \right]^{0.4} \rho^{0.42} V^{0.29}$$

Taylor and McDonnell (Ref. 21), 1997



• Ref. 11

• Ref. 18

◦ Ref. 17

• Ref. 13

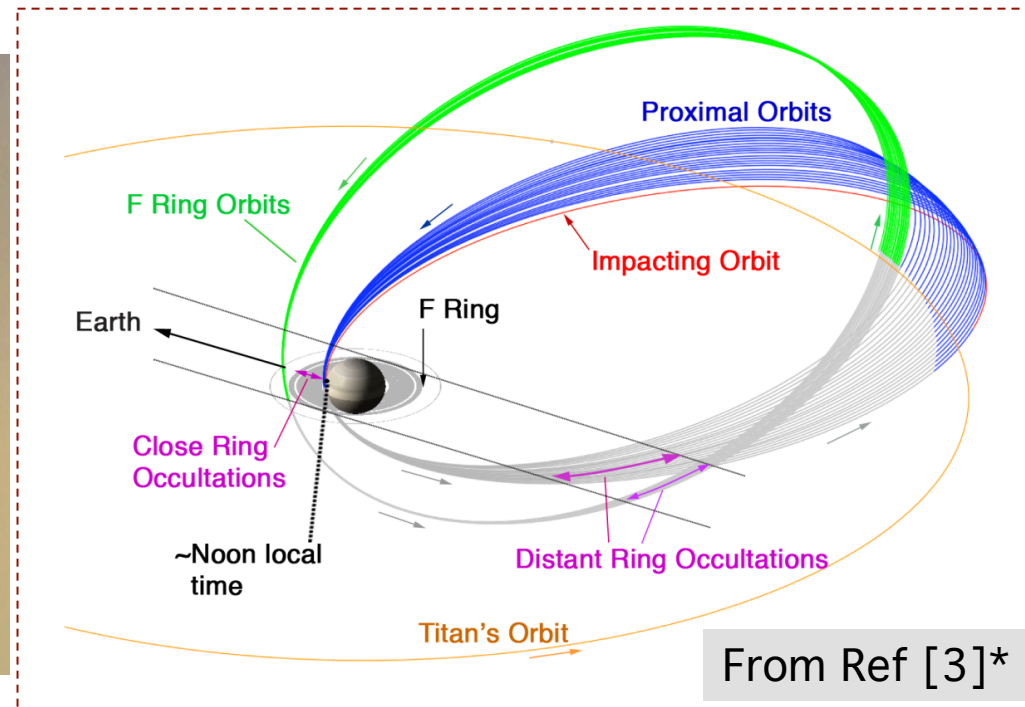
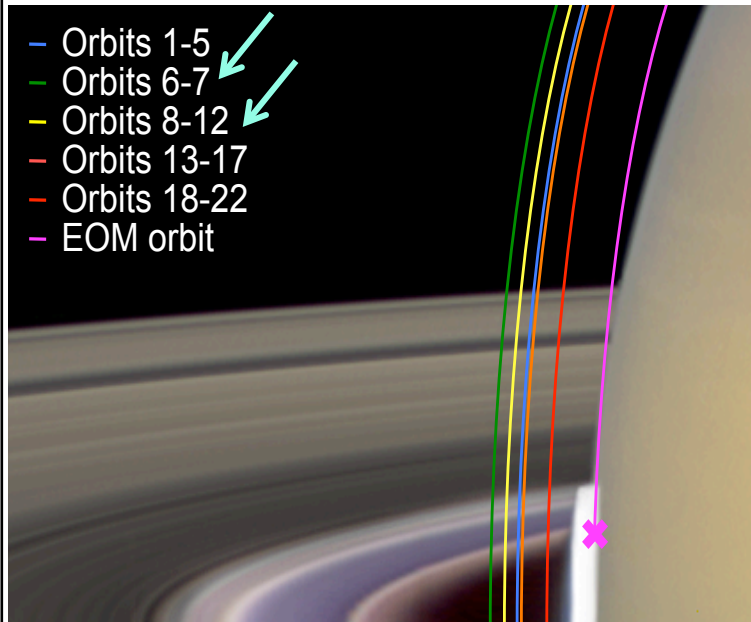
• Ref. 19

◦ Ref. 21

NASA  
Handbook for  
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# Proximal Orbits [Ref. 3\*]

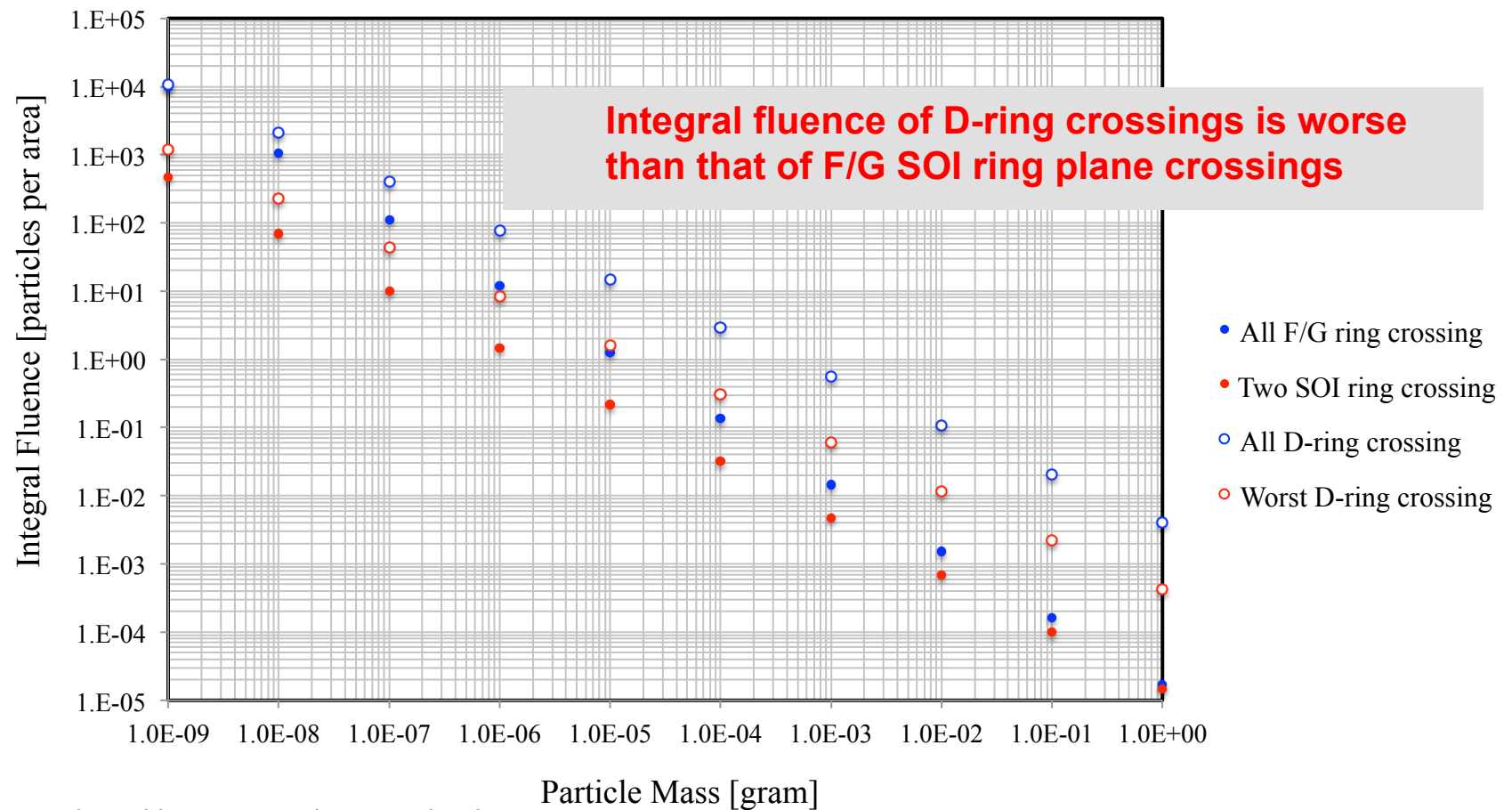
- In late 2016, Cassini will begin a daring set of ballistic orbits that will hop the rings and dive between the upper atmosphere of Saturn and its innermost D-ring 22 times
- In five of the 22 orbits (orbits 1, 6, 7, 11, and 12), the S/C will fly very close to the innermost D-ring. For these orbits, the Cassini mission operations will again employ the HGA-to-RAM pointing strategy. SSA risk must again be assessed:
  - To this end, an estimation of the integral fluence of the D-ring crossings is needed (see next page)
  - Estimated HVI parameters are: Impact velocity is  $\leq 31.4$  km/s, dust density is  $\leq 1$  gram/cm<sup>3</sup>



\*Ref. 3, Burk, T.A., "Cassini at Saturn Proximal Orbits – Attitude Control Challenges," Paper AIAA-2013-4710, Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, August 19–22, 2013, Boston, MA.

## Integral Fluence at F/G (SOI) and D (Proximal) Rings

- Integral fluence for ALL and two SOI ring crossings
- Integral fluence for ALL and the worst D ring crossings\*



\*As contributed by Dave Seal, JPL, Caltech

## Applicability of HVI empirical relations at High Velocity

- HVI empirical relations have been validated against test results with impact velocity of  $<10$  km/s. Are they applicable to the following scenario?
  - HVI velocity as high as 17.1 km/s at SOI
  - HVI velocity as high as 31.4 km/s at proximal orbits
- Ref. 15 documented test results from JSC Hypervelocity Impact Technology Laboratory (HITL) and other test laboratories, up to 10 km/s on a fused silica window system proposed for the Orion spacecraft.
  - Test results were augmented by simulation results performed with the Sandia National Laboratories 3-D **hydrodynamics simulation tools** (to as high as 30 km/s)
- Results from Ref. 15 indicated that predictions made using the above cited empirical relations are conservative for HVI with speeds of 17.1–31.4 km/s (see Appendix A of paper for details)

# Summary of HVI-on-Sun Sensor Cover Glass Results

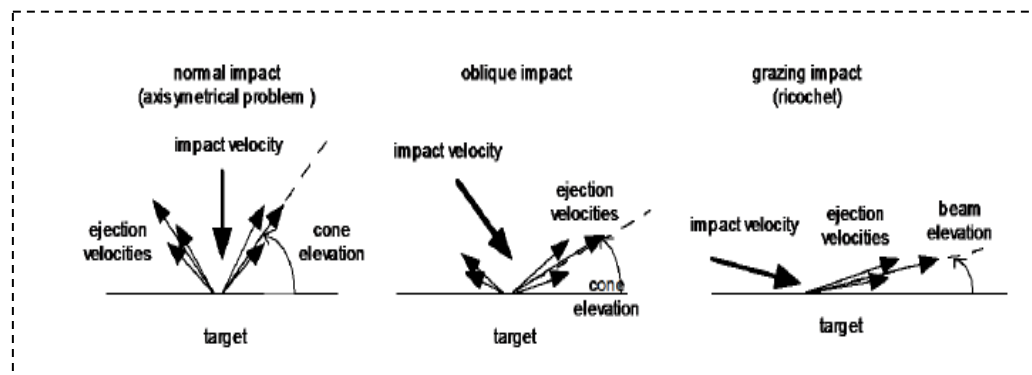
**Table 2 Summary of All Ring Plane Crossing HVI Risk**

<b>F/G Ring Crossings</b>	
Number of particles that can damage SSA cover glass in all F/G ring plane crossings (density is 0.5–2 gram/cc).	7.18e-4 – 1.22e-3 particles
Fraction of SSA cover glass area blacked-out by HVI craters due to total reflection using results from Ref. 11 (density is 0.5–2 gram/cc).	0.037 – 0.064%*
Fraction of SSA cover glass area blacked-out by HVI craters due to total reflection as computed using results from Ref. 18 (density is 0.5–2 gram/cc).	0.083 – 0.089%*
<b>D Ring Crossings</b>	
Number of particles that can damage SSA cover glass in all D ring plane crossings (density is 1 gram/cc).	2.19e-2 particles
Fraction of SSA cover glass area blacked-out by HVI craters due to total reflection (all D-ring plane crossings with density of 1 gram/cc) using results from Ref. 11.	0.998%*
Fraction of SSA cover glass area blacked-out by HVI craters due to total reflection (A single worst-case D-ring crossing with density of 1 gram/cc) using results from Ref. 11.	0.1076%*
Fraction of SSA cover glass area blacked-out by HVI craters due to total reflection (A single worst-case D-ring crossing with density of 1 gram/cc) using results from Ref. 18.	0.4371%*

\*Computed with a factor of 2 margin.

## HVI Risk due to Secondary Debris Covered in this Paper

- Beside being directly impacted by dust particles travelling at high speeds, the Sun sensor covers are also threatened by some fraction of secondary debris that are produced by HVI of dust particles on the large HGA dish
- The damage potential of a ricochet debris particle is a complex function of the spatial distributions of ricochet debris cloud, the ratio of the total ejecta mass relative to the incoming mass, as well as the velocity of the ricochet ejecta
  - These factors are estimated in the paper for the case when Cassini assumed the HGA-to-RAM attitude
  - Details are given in the paper



Schematic representation of debris cone for normal, oblique, and grazing HVI (from Ref. 23)

# Conclusions

- For both F/G and D-ring crossing's:
  - Probability of a **penetration damage** of the SSH window glass is very low
  - **Optical attenuation** due to craters on the surface of the window glass caused by **direct HVI** by dust particle is estimated to be <1%
  - Optical attenuation due to **secondary debris** cloud generated by the disintegrated ring dust particles is estimated to be <1%
- To better manage the Sun sensor damage risk during selected proximal orbit crossings, it is highly desirable to follow the contingency procedures mentioned in Section VII of the paper:
  - Details of this contingency procedure are given in the paper entitled “Cassini operational Sun sensor risk management during proximal orbit Saturn ring Plane crossings” authored by David M. Bates
- Based on results of risk analyses documented in this work and contingency planning work described in the paper mentioned above, we judge that the proximal orbit campaign will be safe from the viewpoint of dust HVI hazard